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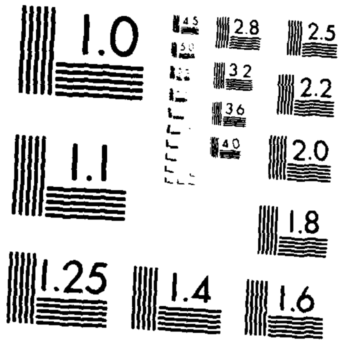

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A STUDY OF DEEP SEA TIDE DETERMINATION
BY SEASAT ALTIMETER DATA

Final Report
Contract N00014-82-C-0368

Prepared for the

Office of Naval Research
Geology and Geophysics Group 425GG
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May 31, 1983

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The objective of this study was to extend the SEASAT altimeter determination of the M2 ocean tide from a single point near Cobb seamount in the northeast Pacific ocean to all the world's oceans on a 5° grid. After extending the grid to 32 locations covering the northeast Pacific ocean, it became apparent that the resulting tidal charts contained unrealistic features. In addition, large discrepancies existed between the altimeter determined parameters and those determined from bottom pressure gauges. Further extension of the altimeter solutions was therefore stopped and the study efforts were

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redirected to study the reason for the discrepancies.

It was concluded that the uncertainty of the altimeter solutions was much higher than originally anticipated, due to the near-resonance of the SEASAT orbit with the dominant tidal components and the relative shortness of the SEASAT mission. The extension of the altimeter tide solution for M2 over the world's oceans requires data from a future altimeter satellite mission spanning at least one year.

BACKGROUND

In the previous contract N00014-79-C-0409, SEASAT altimeter data was analyzed for tidal information at a location in the northeast Pacific ocean near COBB seamount (Brown, [1983]). The amplitude and Greenwich phase angle of the M2 component determined by harmonic analysis of the altimeter sea height residuals were in fair agreement with M2 tide parameters determined using a bottom pressure gauge on Cobb seamount (Larsen and Irish, 1975). The altimeter M2 parameters are 43 $\pm$ 8 cm amplitude and 243 $\pm$ 10 degrees Greenwich phase angle, while the bottom pressure gauge results are 81 cm amplitude and 242^{o} Greenwich phase. In addition, the altimeter solution seemed quite robust. The altimetric tide parameters remained quite consistent as different altimeter passes were deleted from the solution (see Figure 1). The generally reduced amplitude of the altimeter solutions was thought to be due to the use of non-optimum weighting of the different tidal components in the solution.

Encouraged by these results, in the present contract we undertook to extend these altimetric tide solutions for M2 over all the world's oceans, wherever sufficient SEASAT data existed to permit the near coincident intersections of 5 or more north bound passes with 5 or more southbound passes. In general, this would result in a global grid of altimetric tide solutions at an interval of 5^{o}. At these points the altimetric tide parameters would be compared to those interpolated from bottom pressure gauges or other deep ocean tide models.

SUMMARY OF ACTIVITIES

By June of 1982, the altimeter solutions had been extended to eleven locations in the northeast Pacific (Brown, 1982) and while 5 solutions agreed well with nearby bottom pressure gauge results, some systematic discrepancies were observed in the other 5 solutions. By September of 1982, the northeast Pacific grid had been expanded to 32 solutions, and the discrepancies became more frequent and less systematic. These results were described in a paper presented at OCEANS '82 conference, September 20 - 22, 1982 in Washington, D.C. As it was obviously premature to continue the global extension of the solution in the face of these unsolved problems, we decided to analyze the existing solutions in depth. This final report describes the results of that analysis as well as a description of the 32 altimetric tide solutions in the northeast Pacific.

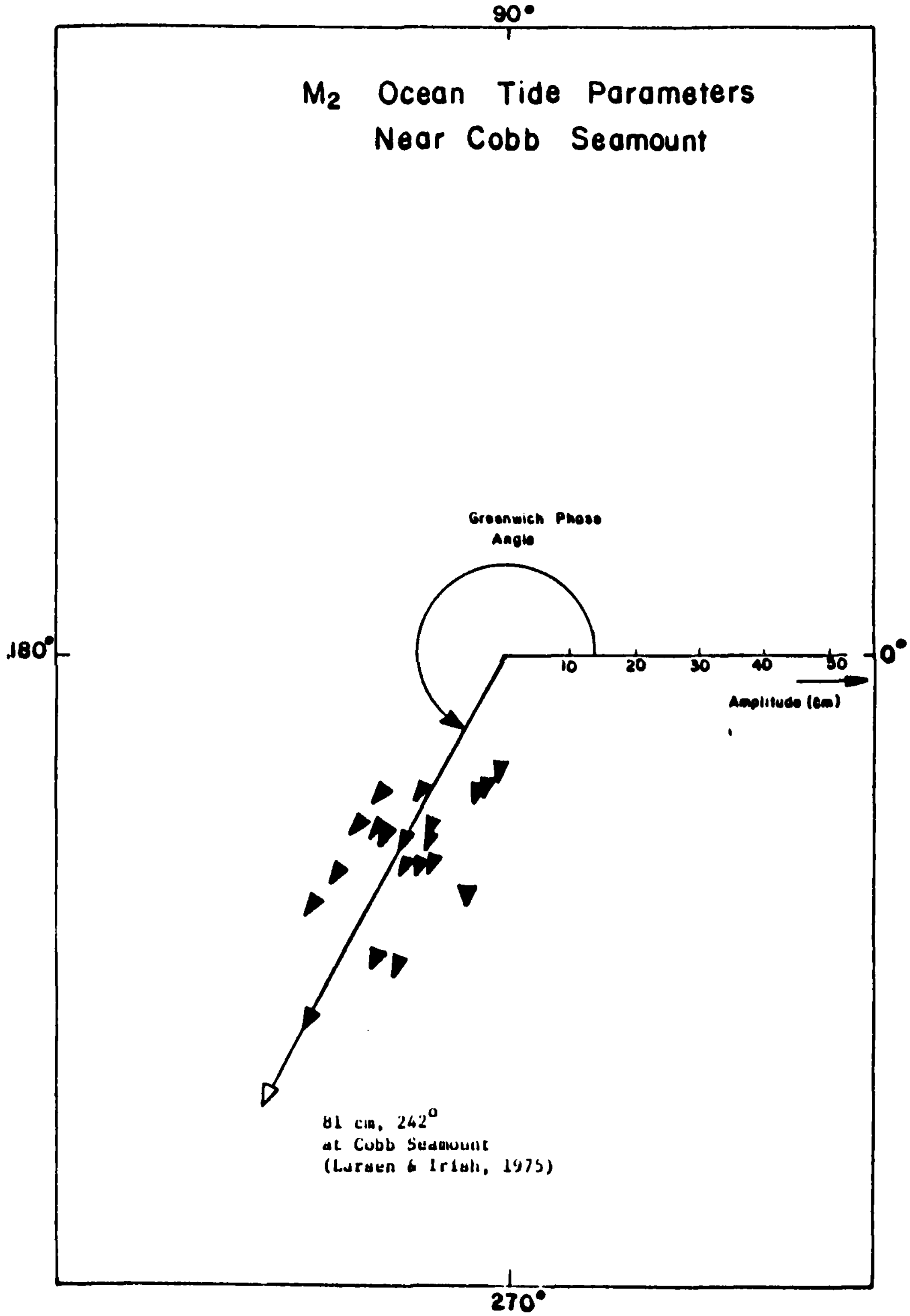
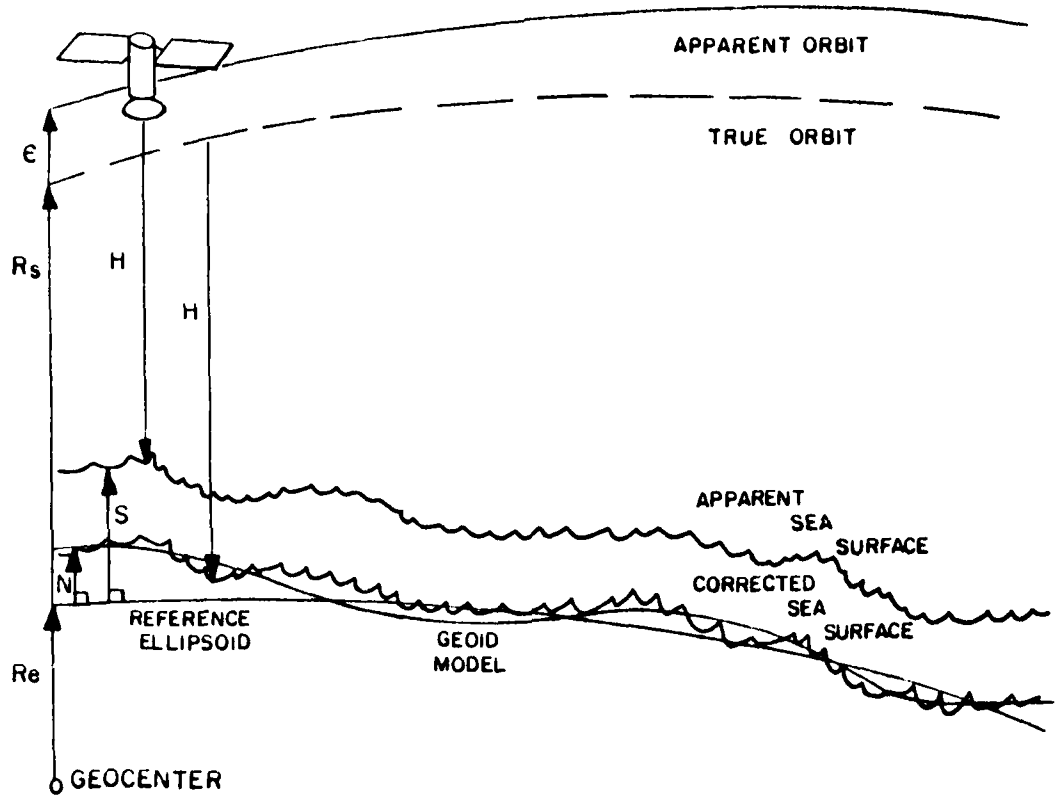

90°
M2 Ocean Tide Parameters
Near Cobb Seamount
Greenwich Phase
Angle
180°
0°
10
20
30
40
50
Amplitude (cm)
81 cm, 242°
at Cobb Seamount
(Larsen & Irish, 1975)
270°

FIGURE 1

DERIVATION OF SEA SURFACE HEIGHTS

Historically, the primary problem for recovery of ocean tides from satellite altimetry is the aliasing of orbit error with derived sea surface height (Brown and Hutchinson, 1981). Figure 2 illustrates this problem.



Alias Between Orbit Error ε and
Derived Sea Surface Height, S.
Figure 2

The error ε in the knowledge of satellite distance Rs from the geocenter, couples directly into the computation for sea surface height S as follows:

$$S = RS - Re - H + \varepsilon \tag{1}$$

where Re is radius to the reference ellipsoid and H is the measured altitude.

The radial (height) component of the satellite orbit error is modeled as a low order harmonic function of the orbit period. It is crucial for the separation of tides from these orbit perturbations that the data arc be longer than a full spatial wavelength of the ocean tide pattern of interest. The data arc length chosen for orbit error removal was 6000 km, corresponding to a time span of 15 minutes at satellite speed along the subtrack. The radial orbit error ε over this time span is modeled as

$$\varepsilon = A + B\cos W_o t + C\sin W_o t + D\cos 2W_o t + E\sin 2W_o t \tag{2}$$

where W_o is the orbital frequency in radians/sec and $t \ll 2\pi/W_o$. For the tidal analysis, we replace the actual geoid height N by a good mathematical model $N_m(t)$, such as GEM-10B (Lerch et al., 1978) at each point of the data arc, and express the difference between the derived sea height and the geoid as

$$S(t) - N_m(t) = \varepsilon(t) + d \tag{3}$$

where d is unmodeled geoid and temporal sea surface heights as well as random noise. An equation 3 is generated for each altimeter observation and these are solved in a least-squares procedure for the optimal parameters A^*, B^*, C^*, D^*, and E^*. The corrected sea surface height,

$$S^*(t) = S(t) - \varepsilon^*(t) \tag{4}$$

is a least squares best fit to the GEM-10B geoid profile along the data arc, with short wavelength residuals due to detailed geoid anomalies and temporal ocean surface variations.

DATA DISTRIBUTION

The three-day repeat orbit of SEASAT results in a locally high concentration of subtrack crossings, occuring on a regular grid spacing at about 8 degrees of longitude.

Figure 3 displays 108 SEASAT arcs with crossovers concentrated in 32 locations. Altimetric tide parameters have been determined for all of these locations. If we label the northbound (southeast-northwest) passes by index i, and the southbound passes by index j, then orbit-corrected sea heights interpolated to these crossovers may be written as

$$
\begin{aligned}
& S^*(t_{ij}) = N(t_{ij}) + T(t_{ij}) + e_{ij} \\
\text{and} \quad & \\
& S^*(t_{ji}) = N(t_{ji}) + T(t_{ji}) + e_{ji}
\end{aligned}
\tag{5}
$$

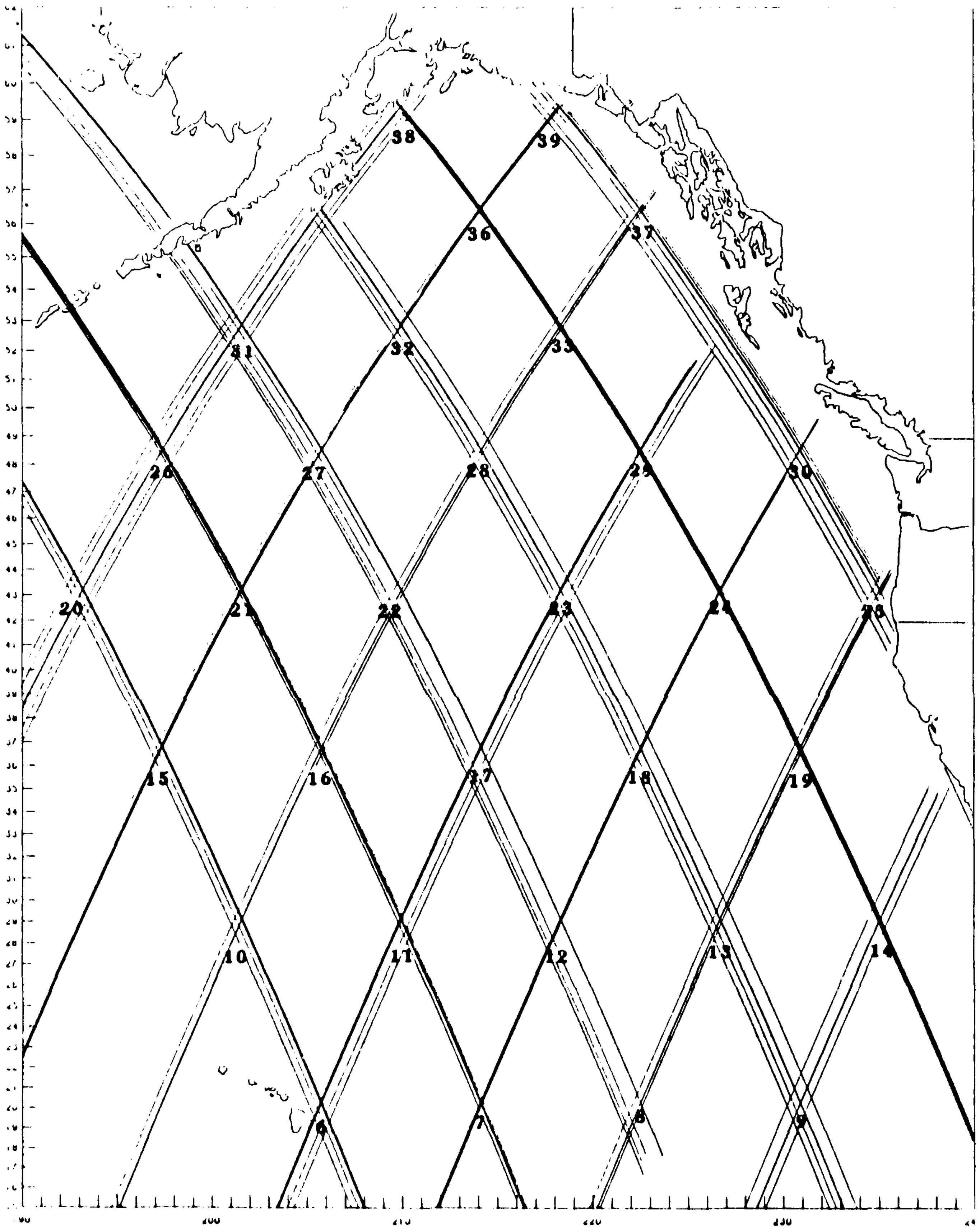
where t_{lm} is the time at which the satellite on subtrack l, overflies track m; $N(t_{lm})$ is the actual geoid height at the crossover point; $T(t_{lm})$ is the height of the ocean tide at the time t_{lm}; and e_{lm} is the non-tidal contribution to sea surface height at this crossover at time t_{lm}, such as due to eddies, inverse barometer effects, and altimeter noise.

While each of these measurements has a unique location and time, their proximity in space and in time (for a given pass), limits the number of essentially different tide heights observed. For recovery of tidal parameters, we will later assume that all the different crossovers in a given locale experience the same tide, but for reducing random altimeter noise effects, let us now consider that this series of measurements represent statistically independent measures of the instantaneous sea height. Note that t_{ij} is not equal t_{ji}, and these times may differ by amounts ranging from several hours to several months.

In general, it is very difficult to extract tidal information from these derived sea heights, because the actual geoid height $N(t_{lm})$ is not accurately known. However, we may apply the constraint

$$N(t_{ij}) = N(t_{ji}) \tag{6}$$

and form difference equations which are independent of knowledge of the actual geoid, as follows:



SEASAT Data tracks and Tide Solution Locations
in the Northeast Pacific
Figure 3

$$\begin{aligned}\Delta S_{ij} &= S^*(t_{ij}) - S^*(t_{ji}) \\ &= T(t_{ij}) - T(t_{ji}) + e'_{ij} \qquad (7)\end{aligned}$$

$$\text{where } e'_{ij} = e_{ij} - e_{ji}$$

HARMONIC ANALYSIS

We model the ocean tide T(t) for all ij by a single linear combination of the 5 largest tidal harmonics, assuming known period but unknown amplitude and phase. Implicitly, we also assume that all the crossovers are collocated each observing the same tide in the local area. Substituting this expansion T in equation 7, we obtain

$$\Delta S_{ij} = \sum_{k=1}^{5} \left[a_k(\sin w_k t_{ij} - \sin w_k t_{ji}) + b_k(\cos w_k t_{ij} - \cos w_k t_{ji})\right] + e'_{ij}$$

where the a_k, b_k are unknown coefficients related to the area mean tidal amplitude A_k and Greenwich phase angle ϕ_k by

$$A_k = \sqrt{a_k^2 + b_k^2}$$

$$\phi_k = \mathrm{Tan}^{-1}\left(\frac{a_k}{b_k}\right) + K_k$$

where K_k is the phase of the kth component of the equilibrium tide at Greenwich at the epoch time 0000hrs GMT, April 30, 1975 (see Schureman, 1941).

Even though we are only interested in the M2 parameters, we parameterize the next largest components (K1, S2, O1, and N2) in order to effect some separation between components which may alias with M2 in such a short time span.

Thus we express the difference in derived sea heights at the subtrack crossovers in terms of differences in tidal phase angles of these 5 components. If the time differences $t_{ij}-t_{ji}$ are such that the essential tidal phase angle differences are well-distributed, then a least-squares solution of the ΔS_{ij} should permit extraction of the tidal information from these measured sea

height differences. For tidal components S2 and K1, the 3 day repeat orbit does not yeild a good distribution of tide phases. This is mitigated by the use of some colinear passes from early in the mission (orbit number less than about 1040) when the orbit track repeat period was not so commensurate with that of ocean tide components.

We seek a least squares estimation of the ten tidal parameters, a_k and b_k, to minimize the sum of squares of the quantities

$$\Delta S_{ij} - \left[T(t_{ij}) - T(t_{ji})\right]$$

The generalized normal equation to be solved is of the form

$$\left[L^T L + W\right] \vec{x} + L^T \vec{\Delta} S \qquad (10)$$

where L is the matrix of coefficients such as

$$\sin w_k t_{ij} - \sin w_k t_{ji}$$

or

$$\cos w_k t_{ij} - \cos w_k t_{ji}$$

$\vec{x}$ is the vector of tidal parameters a_k, b_k, k = 1 to 5; $\vec{\Delta} S$ is the vector of sea height differences $\vec{\Delta} S_{ij}$, and W is an arbitrary weight matrix (2K by 2k).

We find that a diagonal weight matrix [W] is helpful in preventing ill-conditioning, a condition which causes the root-sum-squared of the solution parameters to exceed the observed sea height differences. For a completely unconstrained solution, we set [W]=0. If, on the other hand, we desire negligible adjustment for certain parameters, then the associated weight matrix element for the parameters to be frozen is set to a very large value. Since we know that the M2 amplitude is generally larger than that of the other components, we chose a constraint that influences the assignment of most of the tidal amplitude to the M2 component, with lesser amounts to the other components in proportion to their relative amplitudes in the northeast Pacific (Brown, 1983).

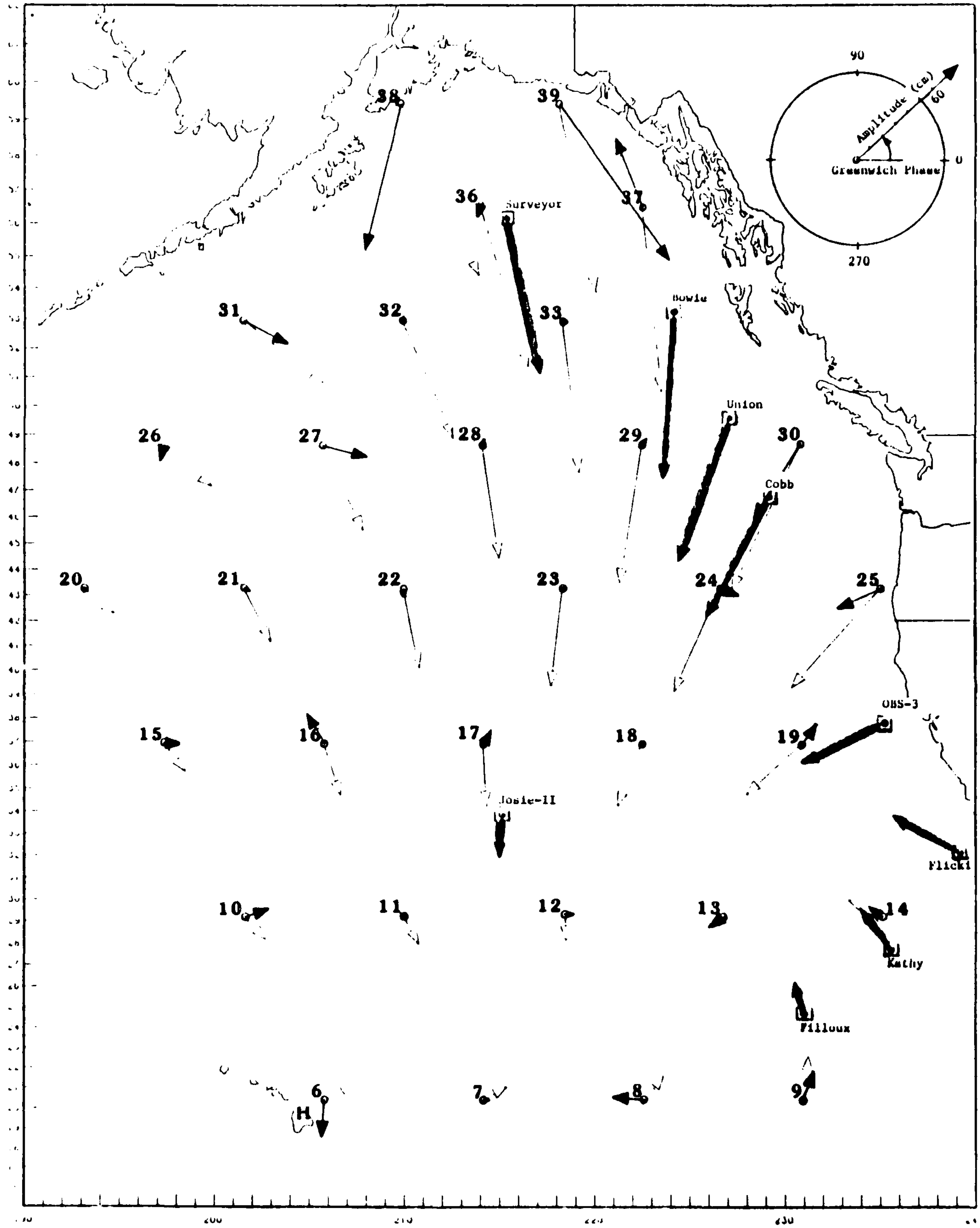
This type of weighting does not force the adoption of a particular value for the amplitude of any given tidal component, but merely guarantees a well-conditioned solution. The exact values of these weights are not critical, and have no direct effect on the M2 parameters. However, the phase angles of the lesser components are distorted by this form of weight matrix.

RESULTS

Altimetric parameters for the M2 tide at all 32 locations in the northeast Pacific are displayed in Figure 4 together with those of nearby bottom pressure gauges.

The northern-most pressure gauges are emplaced on seamounts. From north to south, the Surveyor, Bowie, and Union seamount gauges were reported by Rapatz and Huggett, [1977], while the Cobb seamount gauge results are those of Larsen and Irish, [1975]. The gauge west of San Francisco is the OBS-3 station of Lamont (Nowroozie, 1972) as reported by Schwiderski, [1979]. The gauge furthest from the mainland is Josie-II (Irish, et al., 1971), and the southern-most four stations are Flicki, Josie, Kathy, and Filloux, as reported by Munk, et al., [1970]. All pressure gauges are indicated by name, with the exception of station H, which is a surface tide gauge reported by Schwiderski [1979]. These bottom and surface tide gauge results are generally consistent with the hypothesis of a counter-clockwise rotating amphidromic system about mid-way between Hawii and the mainland.

Numerical values for the altimetric and pressure gauge parameters are listed in Table 1. The altimetric tide parameters are not strictly comparable with the pressure gauge results because the altimetric tide includes the deformation of the solid earth as well as that of the ocean. However, calculations by Parke and Hendershott [1980], show that the contribution of the vertical solid earth tide to M2 in this area is less than about 5 cm in amplitude and essentially no change in phase. Thus, with this level of precision, we may directly compare bottom pressure gauge and altimetric results.



Comparison of Altimetric and
Bottom Pressure Gauge Results
Figure 4

Table 1. Altimetric Tide Parameters
for the Northeast Pacific

Location	No. of Passes	M2 cm(deg.)	Residual RMS (cm) Before/After
H	--	20 (33)	--------
6	17	22(265)	79/71
7	16	3 (8)	37/ 8
8	12	18(175)	65/28
9	18	18 (70)	63/61
Filloux	--	19(107)	--------
10	15	15 (19)	60/57
11	16	3(135)	85/33
12	13	6(354)	25/13
13	16	10(216)	71/70
Kathy	--	29(128)	--------
14	16	10(142)	84/83
Flicki	--	43(150)	--------
15	15	9(358)	43/16
16	17	20(120)	50/47
17	13	10 (63)	23/19
Josie-II	--	27(267)	--------
18	17	3(219)	15/12
19	14	16 (56)	66/24
OBS-3	--	54(206)	--------
20	15	2(271)	37/19
21	16	3(339)	33/32
22	13	3(268)	36/22
23	17	2(273)	39/39
24	16	11(340)	58/34
25	12	27(205)	67/47
26	16	9(253)	19/16
27	12	27(346)	43/31
28	17	4 (61)	39/38
29	15	5 (58)	83/17
Cobb	--	81(242)	--------
Union	--	91(251)	--------
30	15	43(243)	120/76
31	13	30(332)	64/59
32	16	1(252)	9/ 9
33	14	2(350)	16/12
Bowie	--	101(266)	--------
36	13	5(249)	52/30
Surveyor	--	94(282)	--------
37	14	43(112)	71/26
38	11	98(256)	182/138
39	11	111(305)	166/ 84

Altimeter solutions 9, 13, 14, 18, 23, 25, 30, 36, 37, and 39 yield fair to good agreement with the phase angles of nearby bottom gauges, but the amplitude is generally underestimated. Altimeter solutions 6, 11, 12, 17, 19, 24, 28, 29, 32, 33, and 37 seem to exhibit a phase angle lead of 90 to 180 degrees compared to nearby bottom gauges, and again the amplitudes are underestimated. Altimeter solutions 7, 10, 15, 20, 21, 22, 26, 27, and 31 show fair consistency in phase with the phase angles predicted by Schwiderski [1979], shown as gray arrows in Figure 4, while solutions 8, and 16 disagree by almost 180 degrees. Comparing these altimeter solutions with M2 parameters predicted by Schwiderski [1979] for the same locations, the average underestimate of amplitude is 54 percent with an RMS phase difference of 79 degrees. The altimetric amplitudes, contoured in Figure 5, agree in general with the expected increase toward shore and away from the amphidrome center, as shown in the Schwiderski predicted amplitudes, Figure 6.

Despite the general agreement in the patterns of amplitude and phase, there remain many discrepancies in phase, and the region of low amplitudes seems much too large, compared to bottom pressure gauge results. In particular, less than 10 cm amplitude for M2 for the region of solutions 28, 29, 32, 33, and 36 is clearly indicative of a systematic error in the altimeter solutions. The systematic underestimate of amplitude does not appear to be due entirely to excessive weights in the constraint matrix, since amplitudes change only slightly when the constraining weights are removed.

DISCUSSION

The low amplitude problem appears to be partly due to the crossover data itself. A review of the magnitudes of the crossover differences before recovery of tide parameters (see Figure 7) shows a pattern very similar to that of the recovered M2 amplitudes (in Figure 5). It is impossible to recover an M2 amplitude of, say, 80 or 90 cm as at location 32, from crossover differences whose RMS is 9 cm. The RMS of crossover differences, assuming these differences to be due entirely to a single sinusoidal tide component, should be indicative of the peak amplitude of the tide component. Since the RMS of a sinuisoid is just $a/\sqrt{2}$ times its peak amplitude, and the RMS of the crossover differences (the square root of the mean of the squares of the difference between two sinusoidal

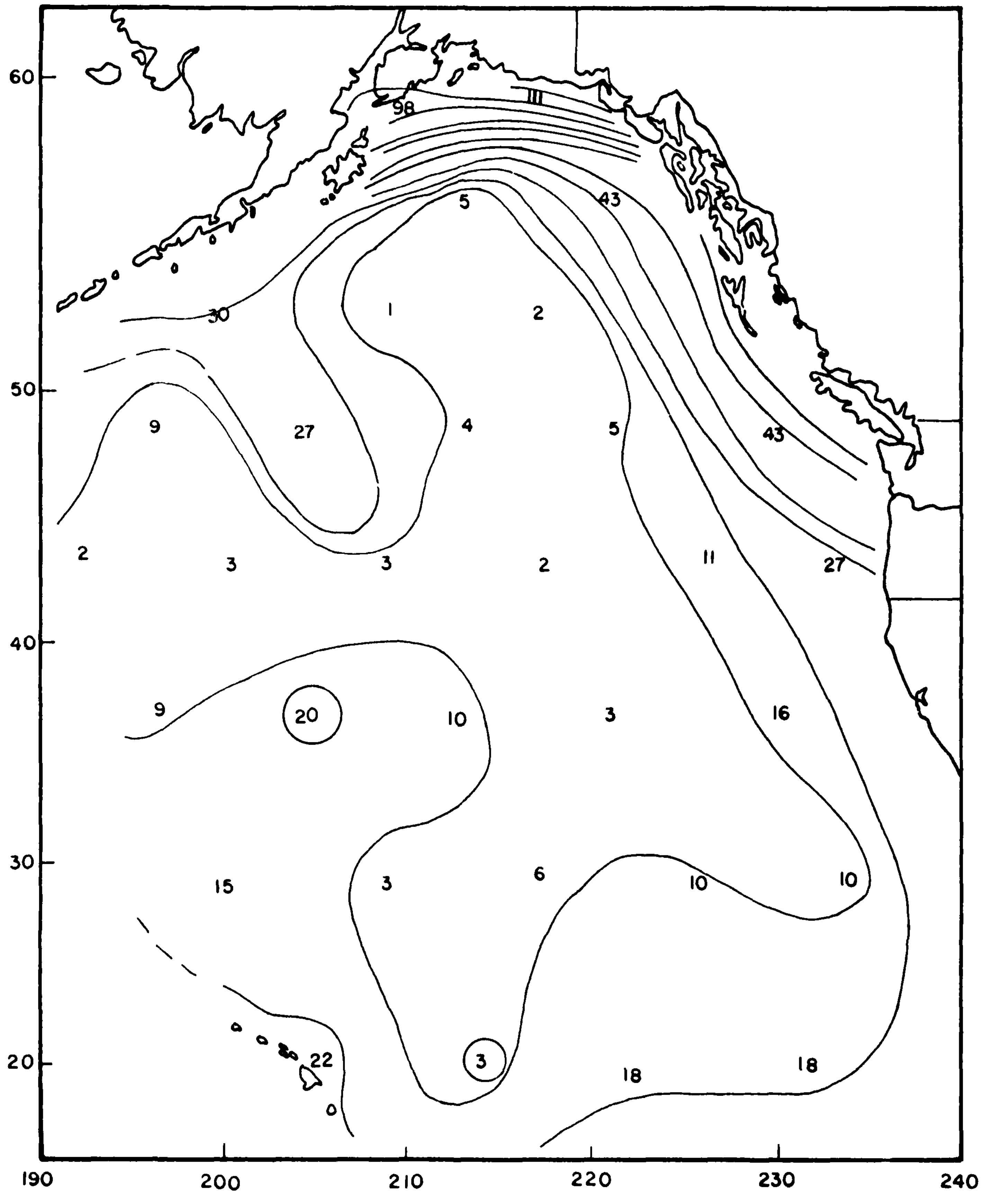


Figure 5

M$_2$ AMPLITUDES FROM ALTIMETER SOLUTIONS
10 cm contour interval

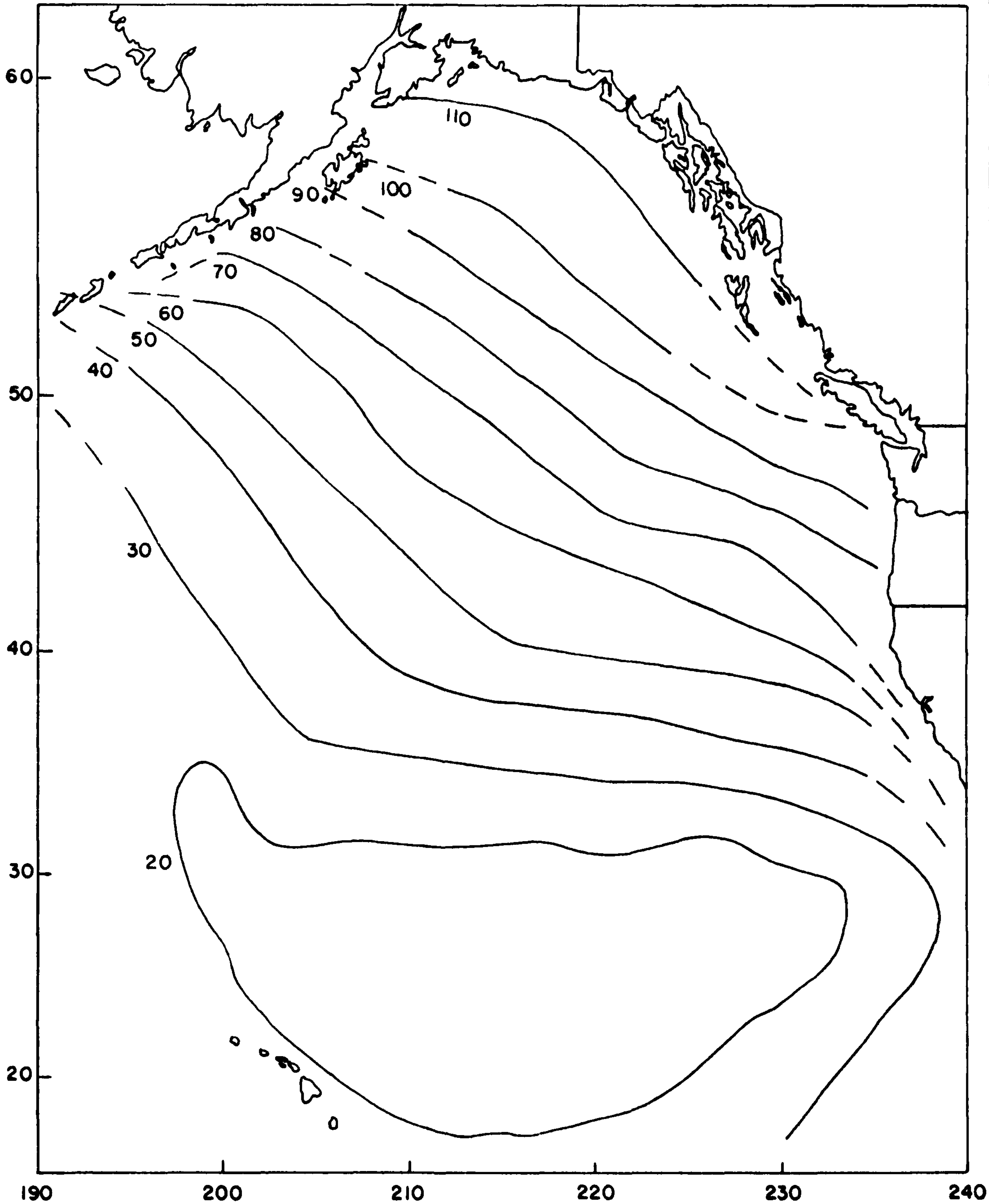
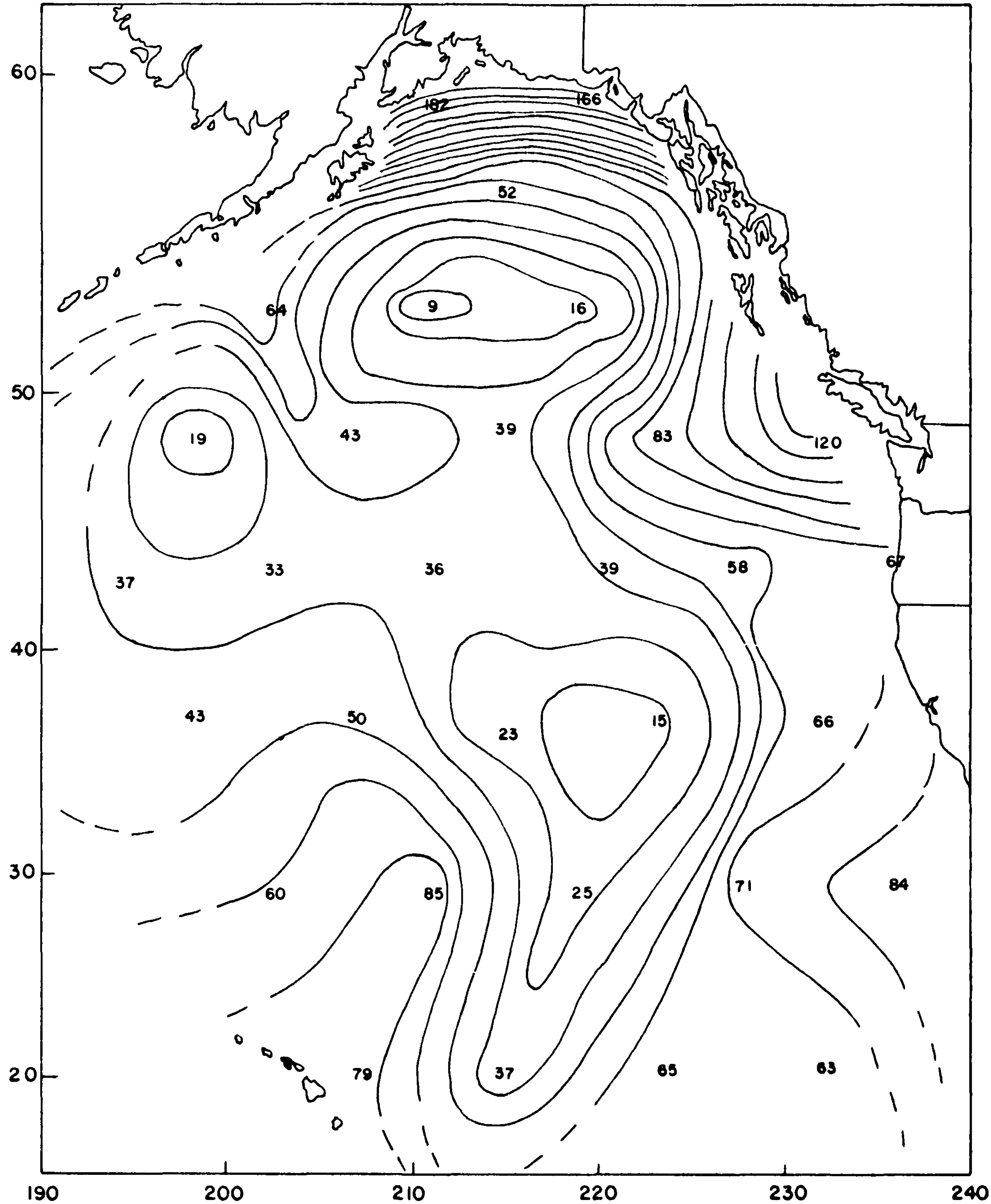


Figure 6

M2 AMPLITUDES FOR SCHWIDERSKI'S SOLUTION
10cm Contour interval



RMS OF CROSSOVER DIFFERENCES

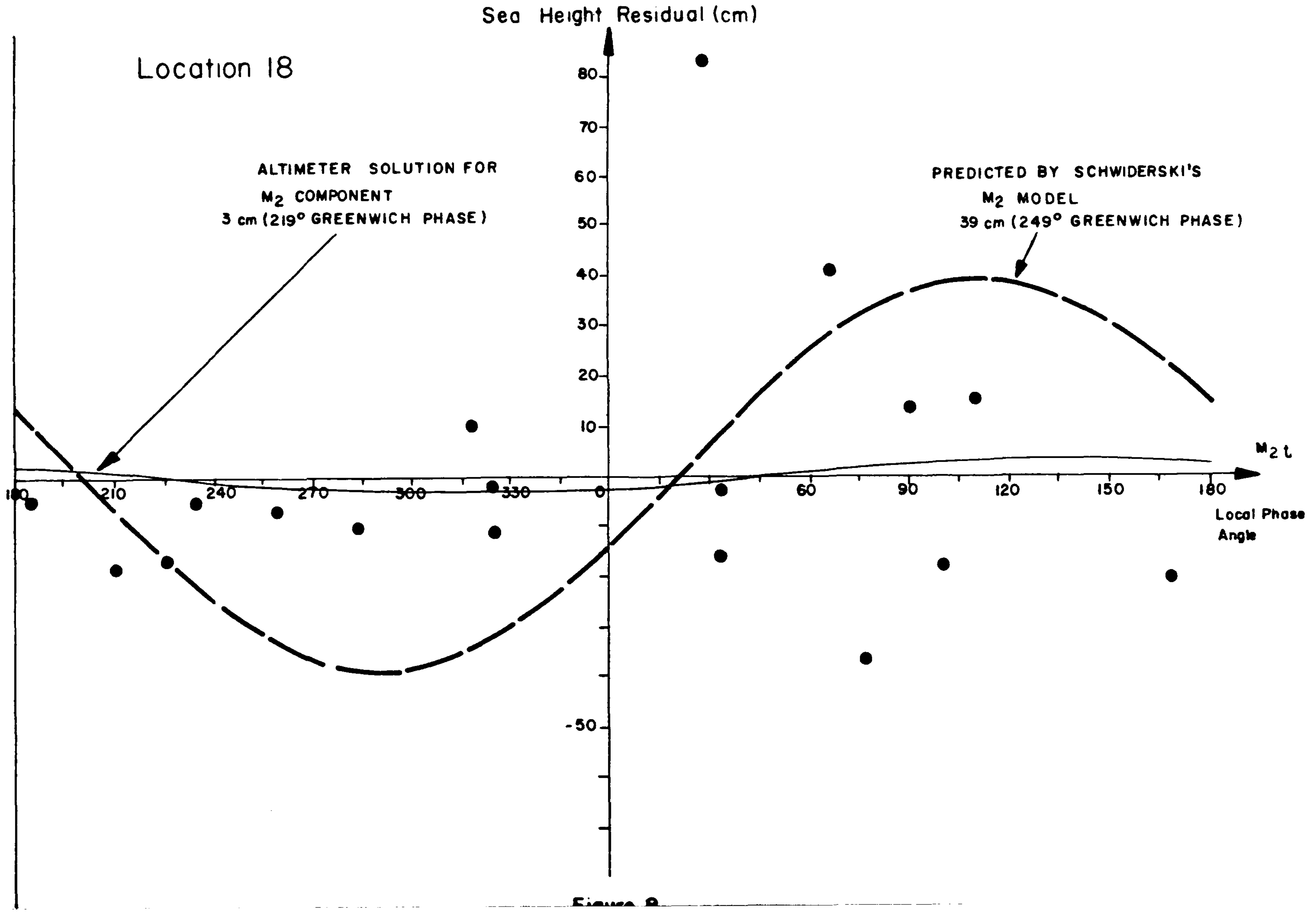
10 cm Contour Intervals

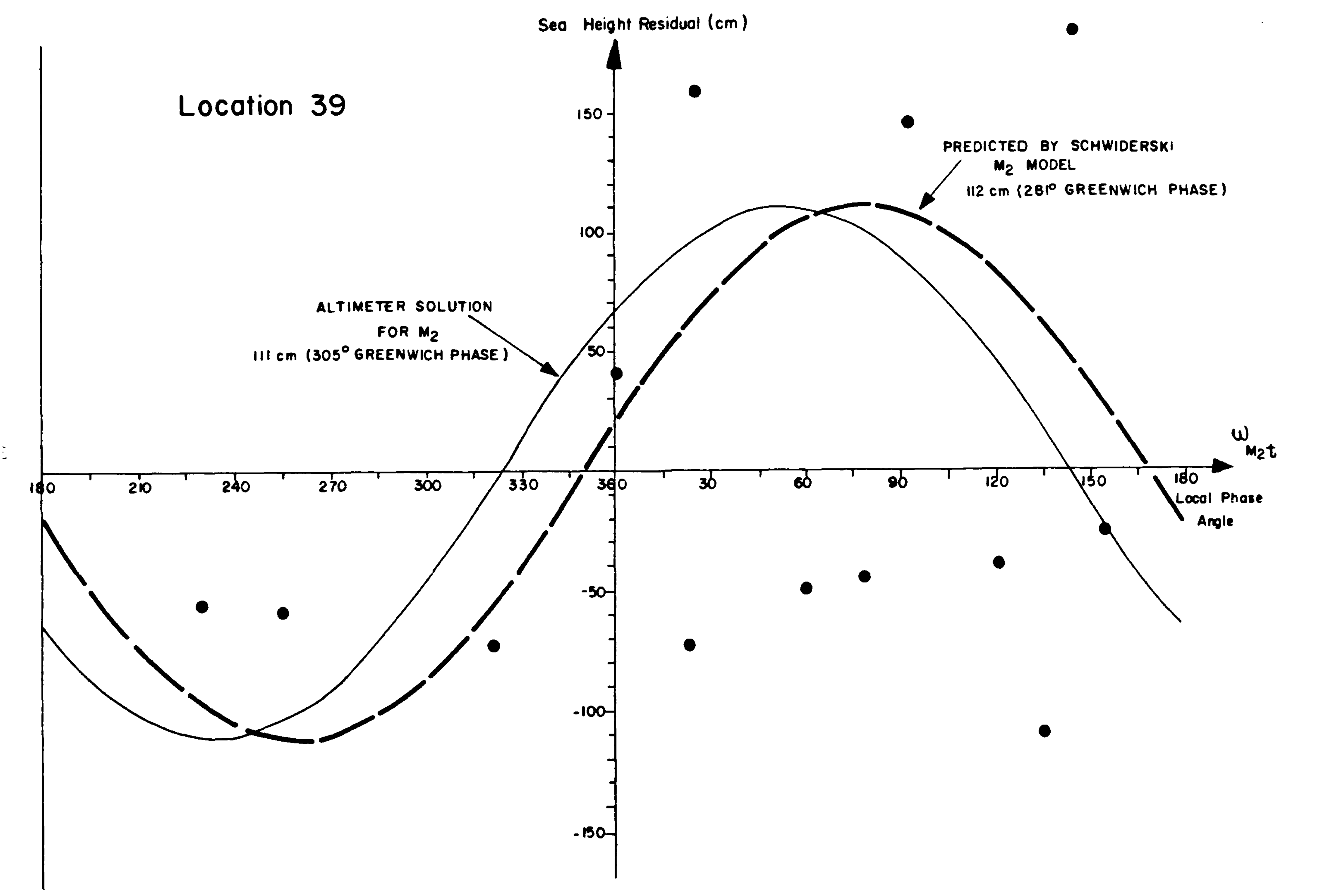
Figure 7

signals of the same amplitude but different phases) is $\sqrt{2}$ times the RMS of a single sinusoidal process, the crossover RMS should ideally be equivalent to the peak amplitude. Of course this assumes no noise and sufficient different samples of phase for accurate representation of the sinusoid. Using the rule-of-thumb that the peak value of a noisy set of data is generally 4 times larger in magnitude than the RMS value of the data set, we assume that our sparse sampling of phase differences permits a maximum possible M2 amplitude of about 4 times the RMS of the crossover differences. This further assumes that only M2 contributes to the crossover differences. By this rule, the observations for location 32 seem to preclude recovery of the M2 amplitude of 77 cm predicted for this location (Schwiderski, [1979]). However, this may be due to an unfortunate distribution of observations.

What then is the reason for such small recovered amplitudes at other locations? A detailed analysis of the crossover differences and their average M2 phase differences reveals a randomness in phase. For example, Figures 8 and 9 show the residuals for locations 18 and 39, together with the sinusoidal signals which result from the altimetric parameters and from the M2 parameters predicted by Schwiderski [1979]. For location 18, Schwiderski predicts an amplitude of 39 cm and a Greenwich phase of 249 degrees. While the crossover differences at location 18 are of sufficient magnitude to support an M2 amplitude of this size, their phases show a randomness that the harmonic analysis interprets as near-zero amplitude at the M2 period. Even when the agreement between the altimeter parameters and Schwiderski's predicted parameters is good, as at location 39 shown in Figure 9, this result is largely due to good fortune. The residuals show a great deal of randomness at the M2 period, and the recovered M2 parameters are supported by only a few of the crossover differences. The same situation holds for all 32 altimetric tide solutions.

Since the only error source that can be characterized as random in this process is that of the altimeter itself, and since the magnitude of this error is only 6-15 cm RMS (Townsend, [1980]), the observed randomness at the M2 period must be due to aliasing with the other harmonic processes affecting the derived sea height. These are the orbital error, with a period of 3/43 days, and the other tidal components, with periods very close to 1 day and 1/2 days.


Sea Height Residual (cm)
Location 18
ALTIMETER SOLUTION FOR
M_2 COMPONENT
3 cm (219° GREENWICH PHASE)
PREDICTED BY SCHWIDERSKI'S
M_2 MODEL
39 cm (249° GREENWICH PHASE)
80
70
60
50
40
30
20
10
0
-50
180
210
240
270
300
330
0
60
90
120
150
180
$M_2 t$
Local Phase Angle
Figure 8



Location 39
Sea Height Residual (cm)
150
100
50
-50
-100
-150
PREDICTED BY SCHWIDERSKI
M2 MODEL
112 cm (281° GREENWICH PHASE)
ALTIMETER SOLUTION
FOR M2
111 cm (305° GREENWICH PHASE)
ω M2t
180 210 240 270 300 330 360 30 60 90 120 150 180
Local Phase
Angle

Figure 9

If the contribution of these sources to the crossover difference could be removed exactly, then the residuals shown in Figures 8 and 9 would presumably appear much less random. Unfortunately, we don't have enough different phase samples to allow reliable separation of these competing harmonic processes. For a location with 15 passes, there are essentially only 14 different phase differences at any given frequency. To separate the 5 competing tidal component periods, we should have 50 to 100 well-distributed phase differences for each period. This may well require several hundred passes of data. Since the SEASAT mission lasted only 100 days, we will need at least a year or two years worth of altimeter data from a future altimeter satellite mission to complete the global altimetric tide solution.

It is possible that the randomness is partly due to incomplete removal of orbit error. In particular, there is a possibility of systematic bias differences between North-bound and South-bound passes which could alias with the tidal signals. This possibility was examined and, while North-South bias differences were found ranging from 0 to 81 cm with an average of 39 cm, removal of these biases change of the M2 parameters (less than 10 cm in amplitude and 10^{o} in phase. Apparently the N-S bias does not alias strongly with the M2 period.

CONCLUSIONS AND RECOMMENDATIONS

The altimetric tide results for M2 exhibit fair agreement with the bottom pressure gauge results at Cobb seamount, and at 10 of 21 locations near bottom pressure gauges. However, phase recover at 13 of the 32 locations is in error by greater than 90 degrees, and the amplitudes of the M2 tide are grossly underestimated for all but 2 or 3 locations. These poor results are thought to be due to aliasing between the M2 tide and other tide components. This aliasing might be corrected by additional observations at different phase angles, but there are no more SEASAT data.

The consistency of the altimeter solutions shows promise for future improved remote measurement of ocean tides. There is still a great deal of room for improvement in the quantity and quality of the altimeter data, the choice of orbit repeat periods, and the techniques for orbit correction and harmonic analysis. It is heartening that such good results have been obtained

with the rudimentary harmonic analysis used here. Perhaps altimeter data from a future satellite mission such as GEOSAT will be sufficiently well distributed in time and of sufficient quantity and duration to prove the independent recovery of ocean tides without exact knowledge of the satellite orbit or local ocean tide parameters.

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